

# Attacks on Implementations of Secure Systems

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# Foreword

This document contains the collected scribe notes created by the students of my course titled "Attacks on Secure Implementations", given in Ben-Gurion University during Spring 2019.

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# Bibliography

- [1] Us navy crypto equipment - 1950's-60's. <http://www.navy-radio.com/crypto.htm>.
- [2] Ryan Singel. Declassified nsa document reveals the secret history of tempest. <https://www.wired.com/2008/04/nsa-releases-se/>.
- [3] memcmp(3) - linux man page. <https://linux.die.net/man/3/memcmp>.
- [4] Flavio D Garcia, Gerhard de Koning Gans, Ruben Muijers, Peter Van Rossum, Roel Verdult, Ronny Wichers Schreur, and Bart Jacobs. Dismantling mifare classic. In *European symposium on research in computer security*, pages 97–114. Springer, 2008.
- [5] Nicolas Courtois, Karsten Nohl, and Sean O’Neil. Algebraic attacks on the crypto-1 stream cipher in mifare classic and oyster cards. *IACR Cryptology ePrint Archive*, 2008:166, 2008.
- [6] Signal amplification relay attack (sara). <https://hackernoon.com/signal-amplification-relay-attack-sara-609ce6c20d4f>.
- [7] What is an fpga? <https://www.xilinx.com/products/silicon-devices/fpga/what-is-an-fpga.html>.
- [8] Amir Moradi, Alessandro Barenghi, Timo Kasper, and Christof Paar. On the vulnerability of fpga bitstream encryption against power analysis attacks: extracting

- keys from xilinx virtex-ii fpgas. In *Proceedings of the 18th ACM conference on Computer and communications security*, pages 111–124. ACM, 2011.
- [9] Confidentiality, integrity, and availability. [https://developer.mozilla.org/en-US/docs/Web/Security/Information\\_Security\\_Basics/Confidentiality,\\_Integrity,\\_and\\_Availability](https://developer.mozilla.org/en-US/docs/Web/Security/Information_Security_Basics/Confidentiality,_Integrity,_and_Availability).
- [10] Hsiao-Ying Lin and Wen-Guey Tzeng. An efficient solution to the millionaires’ problem based on homomorphic encryption. In *International Conference on Applied Cryptography and Network Security*, pages 456–466. Springer, 2005.
- [11] Paul C Kocher. Timing attacks on implementations of diffie-hellman, rsa, dss, and other systems. In *Annual International Cryptology Conference*, pages 104–113. Springer, 1996.
- [12] Atm card blocked after certain numbers of wrong pin.
- [13] Burt Kaliski. The mathematics of the rsa public-key cryptosystem. *RSA Laboratories*, 2006.
- [14] Wikipedia. Rsa (cryptosystem), 2019.
- [15] Jonathan Katz, Alfred J Menezes, Paul C Van Oorschot, and Scott A Vanstone. *Handbook of applied cryptography*. CRC press, 1996.
- [16] Pei Dingyi, Salomaa Arto, and Ding Cunsheng. *Chinese remainder theorem: applications in computing, coding, cryptography*. World Scientific, 1996.
- [17] Henry S Warren. *Hacker’s delight*. Pearson Education, 2013.
- [18] Jean-Francois Dhem, Francois Koeune, Philippe Alexandre Leroux, Patrick Mestré, Jean-Jacques



- Quisquater, and Jean-Louis Willems. A practical implementation of the timing attack. In *International Conference on Smart Card Research and Advanced Applications*, pages 167–182. Springer, 1998.
- [19] Wikipedia. Student’s t-test, 2019.
- [20] Wikipedia. William sealy gosset, 2019.
- [21] Marc F Witteman, Jasper GJ van Woudenberg, and Federico Menarini. Defeating rsa multiply-always and message blinding countermeasures. In *Cryptographers’ Track at the RSA Conference*, pages 77–88. Springer, 2011.
- [22] K. Shirriff. Ken shirriff’s blog. <http://www.righto.com/2013/09/intel-x86-documentation-has-more-pages.html>.
- [23] Colin Percival. Cache missing for fun and profit. *BSD-Can 2005*, 2005.
- [24] Gabriele Paoloni. How to benchmark code execution times on intel® ia-32 and ia-64 instruction set architectures. *White Paper*, 2010.
- [25] David Gullasch, Endre Bangerter, and Stephan Krenn. Cache games – bringing access-based cache attacks on aes to practice. In *Proceedings of the 2011 IEEE Symposium on Security and Privacy*, SP ’11, pages 490–505, Washington, DC, USA, 2011. IEEE Computer Society.
- [26] Dag Arne Osvik, Adi Shamir, and Eran Tromer. Cache attacks and countermeasures: The case of aes. In *Proceedings of the 2006 The Cryptographers’ Track at the RSA Conference on Topics in Cryptology*, CT-RSA’06, pages 1–20, Berlin, Heidelberg, 2006. Springer-Verlag.
- [27] Falkner Yarom. Flush+reload: a high resolution, low noise, l3 cache side-channel attack. *23rd USENIX Security Symposium*, 2014.

- [28] Fangfei Liu, Yuval Yarom, Qian Ge, Gernot Heiser, and Ruby B. Lee. Last-level cache side-channel attacks are practical. In *Proceedings of the 2015 IEEE Symposium on Security and Privacy*, SP '15, pages 605–622, Washington, DC, USA, 2015. IEEE Computer Society.
- [29] Clémentine Maurice, Nicolas Le Scouarnec, Christoph Neumann, Olivier Heen, and Aurélien Francillon. Reverse engineering intel last-level cache complex addressing using performance counters. In Herbert Bos, Fabian Monrose, and Gregory Blanc, editors, *Research in Attacks, Intrusions, and Defenses - 18th International Symposium, RAID 2015, Kyoto, Japan, November 2-4, 2015, Proceedings*, volume 9404 of *Lecture Notes in Computer Science*, pages 48–65. Springer, 2015.
- [30] C. Maurice. Cache template attacks. [https://github.com/clementine-m/cache\\_template\\_attacks](https://github.com/clementine-m/cache_template_attacks).
- [31] Mangard Gruss, Spreitzer. Cache template attacks: Automating attacks on inclusive last-level caches. *24th USENIX Security Symposium*, 2015.
- [32] D. Gruss. Cache template attacks. [https://github.com/IAIK/cache\\_template\\_attacks](https://github.com/IAIK/cache_template_attacks).
- [33] Hamming weight. [https://en.wikipedia.org/wiki/Hamming\\_weight](https://en.wikipedia.org/wiki/Hamming_weight).
- [34] [https://en.wikipedia.org/wiki/Pearson\\_correlation\\_coefficient](https://en.wikipedia.org/wiki/Pearson_correlation_coefficient).
- [35] K. Nohl et al. Reverse-engineering a cryptographic rfid tag. In *17th USENIX Security Symposium*, volume 17. USENIX, 2008. Online; [https://www.usenix.org/legacy/events/sec08/tech/full\\_papers/nohl/nohl.pdf](https://www.usenix.org/legacy/events/sec08/tech/full_papers/nohl/nohl.pdf).
- [36] A. Govindavajhala, S. & Appel. Using memoryerrors to attack a virtual machine. Princeton University. Online; <https://www.cs.princeton.edu/~appel/papers/memerr.pdf>.

- [37] CHDK Wiki. Obtaining a firmware dump. CHDK Wiki. Online; [https://chdk.fandom.com/wiki/Obtaining\\_a\\_firmware\\_dump#Q.\\_How\\_can\\_I\\_get\\_a\\_firmware\\_dump.3F](https://chdk.fandom.com/wiki/Obtaining_a_firmware_dump#Q._How_can_I_get_a_firmware_dump.3F).
- [38] HackingHood. Canon sd300 camera analysis. HackingHood. Online; <https://sites.google.com/site/hackinghood2/home>.
- [39] D. Boneh et al. On the importance of eliminating errors in cryptographic computations. Dept. of Computer Science, Stanford University. Online; <https://link.springer.com/content/pdf/10.1007/s001450010016.pdf>.
- [40] M. Joye et al. Chinese remaindering based cryptosystems in the presence of faults. UCL Crypto Group, Dep. de Mathematique, Universite de Louvain. Online; <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.55.5491&rep=rep1&type=pdf>.
- [41] Schmidt J.M. & Hutter M. Optical and em fault-attacks on crt-based rsa: Concrete results. Institute for Applied Information Processing and Communications, Graz University of Technology. Online; [https://online.tugraz.at/tug\\_online/voe\\_main2.getvolltext?pCurrPk=32877](https://online.tugraz.at/tug_online/voe_main2.getvolltext?pCurrPk=32877).
- [42] Y. Kim et al. Flipping bits in memory without accessing them: An experimental study of dram disturbance errors. Intel Labs, Carnegie Mellon University. Online; <https://users.ece.cmu.edu/~yoonguk/papers/kim-isca14.pdf>.
- [43] K. Razavi et al. Flip feng shui: Hammering a needle in the software stack. Vrije Universiteit Amsterdam. Online; <https://www.cs.vu.nl/~herbertb/download/papers/flip-feng-shui.bheu16.pdf>.
- [44] L. Cojocar et al. Exploiting correcting codes: On the effectiveness of ecc memory against rowhammer attacks. Vrije Universiteit Amsterdam. Online; <https://cs.vu.nl/~lcr220/ecc/ecc-rh-paper-sp2019-cr.pdf>.

- [45] CVE-2017-0144. Available from MITRE, CVE-ID CVE-2017-0144. Online; <https://cve.mitre.org/cgi-bin/cvename.cgi?name=CVE-2017-0144>.
- [46] Coordinated vulnerability disclosure. Online; <https://query.prod.cms.rt.microsoft.com/cms/api/am/binary/RW5Alv>.
- [47] Clemens Lode. *Philosophy for Heroes: Knowledge*. Clemens Lode Verlag e.K., 2016.
- [48] Clemens Lode. *Philosophy for Heroes: Continuum*. Clemens Lode Verlag e.K., 2017.